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Machine Dynamics Branch Research and Accomplishments for FY 1996

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Introduction

As one of the five branches in NASA Lewis Research Center's Structures and Acoustics Division, the Machine Dynamics Branch conducts basic and applied research in dynamics and aeroelastic behaviors of advanced propulsion and power systems as well as of precision mechanical systems. Research is conducted in house, through university grants and contracts, and through cooperative programs with industry. Our work directly supports NASA's Advanced Subsonic Technology (AST), Smart Green Engine (SGE), Fast Quiet Engine (FQE), and Physics & Process Modeling (PPM) base research projects. This work can be broadly classified into four major activities: turbomachinery aeroelasticity, vibration control, dynamic systems response and analysis, and computational structural methods.

In turbomachinery aeroelasticity, we are developing improved analytical and experimental methods for avoiding flutter and minimizing the forced vibration response of aerospace systems. Work elements include classical (frequency domain) methods, time domain methods, computational methods for fluid-coupled structural response, experimental methods, and application studies (turboprop, turbofan, turbopump, compressors, and advanced core technology).

In vibration control, we are developing real-time, actively controlled bearing support systems for advanced aircraft turbine engines. Such support systems will reduce advanced aircraft turbine engine weight and rotor vibrations, improve efficiency, and possibly increase stall margins. We are involved in producing expert system controllers that use advanced computer architectures to adaptively change flight conditions and to monitor the health of the support systems. Technically advanced magnetic bearing technology is focused on achieving higher load capacity, higher operating temperatures, and lower power losses. Research also is ongoing in vibration isolation systems for automobiles, aircraft engines, and in-space laboratory devices: piezoelectric and magnetic actuators are key technologies in this area.

In dynamic systems response and analysis, we are analyzing and verifying the dynamics of interacting systems as well as developing concepts and methods for controlling motion in space and microgravity environments. We also are conducting applied technology research to develop advanced aircraft and spacecraft mechanical components and to solve current operational problems. Development of mechanism standards for the aerospace industry is of particular concern.

In computational structural methods, we are developing advanced programs for analyzing, predicting, and controlling the stability and dynamic response of aerospace propulsion and power system components such as rotating bladed structural assemblies, engine rotors, high-speed shafting, and the coupled interactions of blade-disk-shaft-casing structural systems. In particular, we are developing and employing computational methods to analyze the complex interacting dynamics of advanced turbomachinery and engine components such as fans, compressors, turbines, and turbopumps. This work should fundamentally improve the use of modern computers for solving realistic machine dynamic problems.

George L. Stefko

Branch Manager

Contents

Dynamic Spin Rig Magnetic Suspension

NASA Lewis' Dynamic Spin Rig, located in Building 5, Test Cell CW–18 (see fig. 1), is used to test turbomachinery blades and components by rotating them in a vacuum chamber. This year, a team from the Machine Dynamics Branch successfully integrated a magnetic bearing and control system into the Dynamic Spin Rig (fig. 2). The magnetic bearing worked very well both to support and shake the shaft. Also, our team demonstrated that the magnetic bearing can transmit more vibrational energy into the shaft and excite some blade modes to larger amplitudes than the existing electromagnetic shakers can. Experiments were successfully conducted with the University of California, San Diego, on the damping of composite plates. These experiments demonstrated the system's robustness for long-term testing. Existing magnetic bearing system hardware and software were modified to enhance capabilities, and new features were added, such as a user-friendly interface and flexibility in applying the excitation force in orientation and phasing. We discovered that the bearing can use feedback from blade strain gauges to provide blade damping. This is an additional benefit since insufficient blade damping is a critical problem in advanced turbomachinery blades. The success of the initial work led to the design of a full magnetic suspension system for the Dynamic Spin Rig, which is scheduled for implementation by September 1997. The upgraded facility will provide either a mechanical or magnetic support system for rotors. The magnetic support will enable longer run times for rotating blades at higher speeds and larger vibration amplitudes.

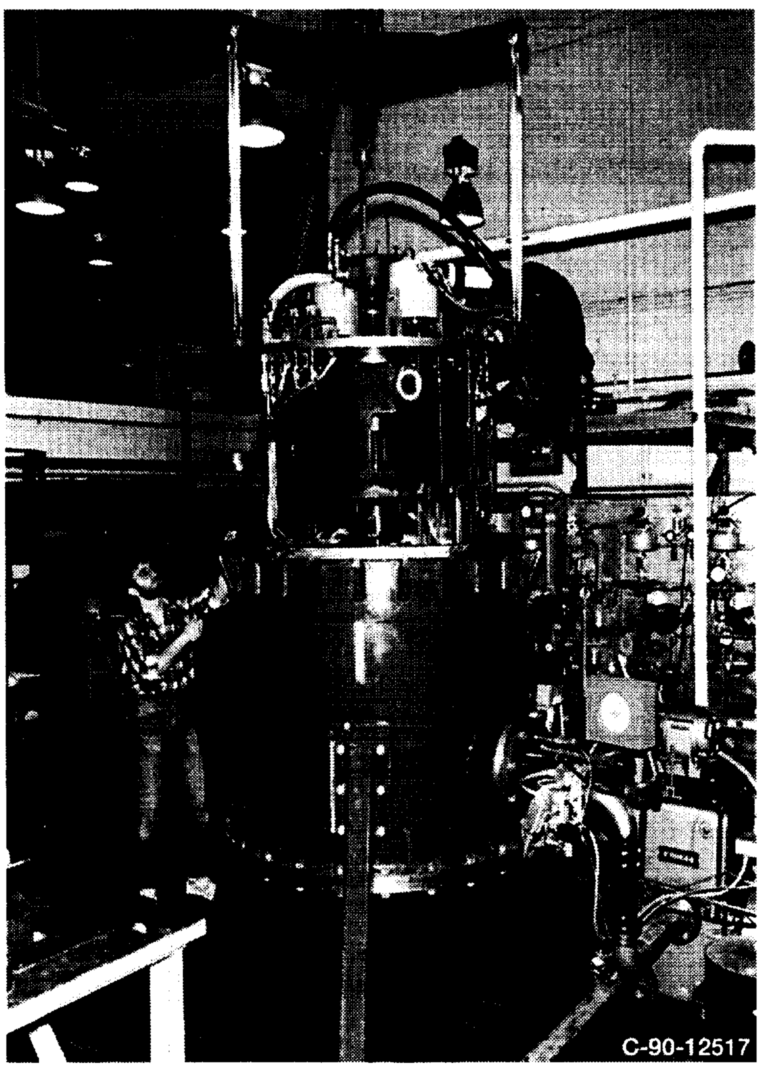

Figure 1.—NASA Lewis' Dynamic Spin Rig.

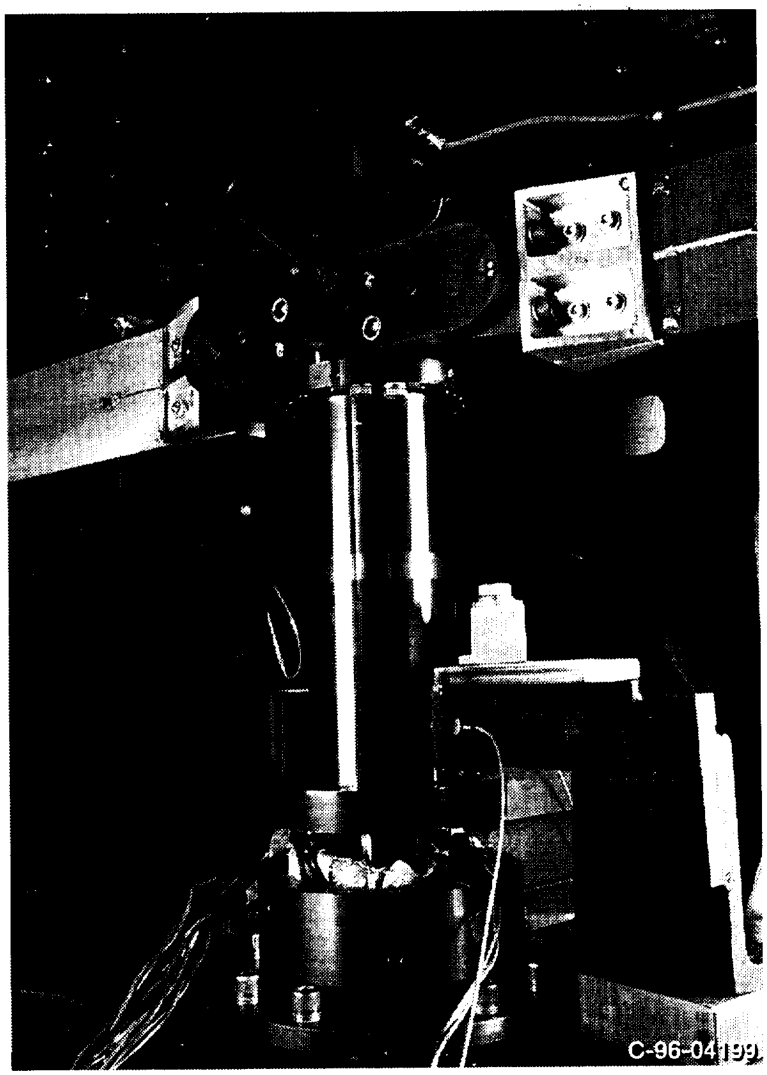

Figure 2.—Radial magnetic bearing in the Dynamic Spin Rig showing viscoelastic damped composite plates attached to the rotor.

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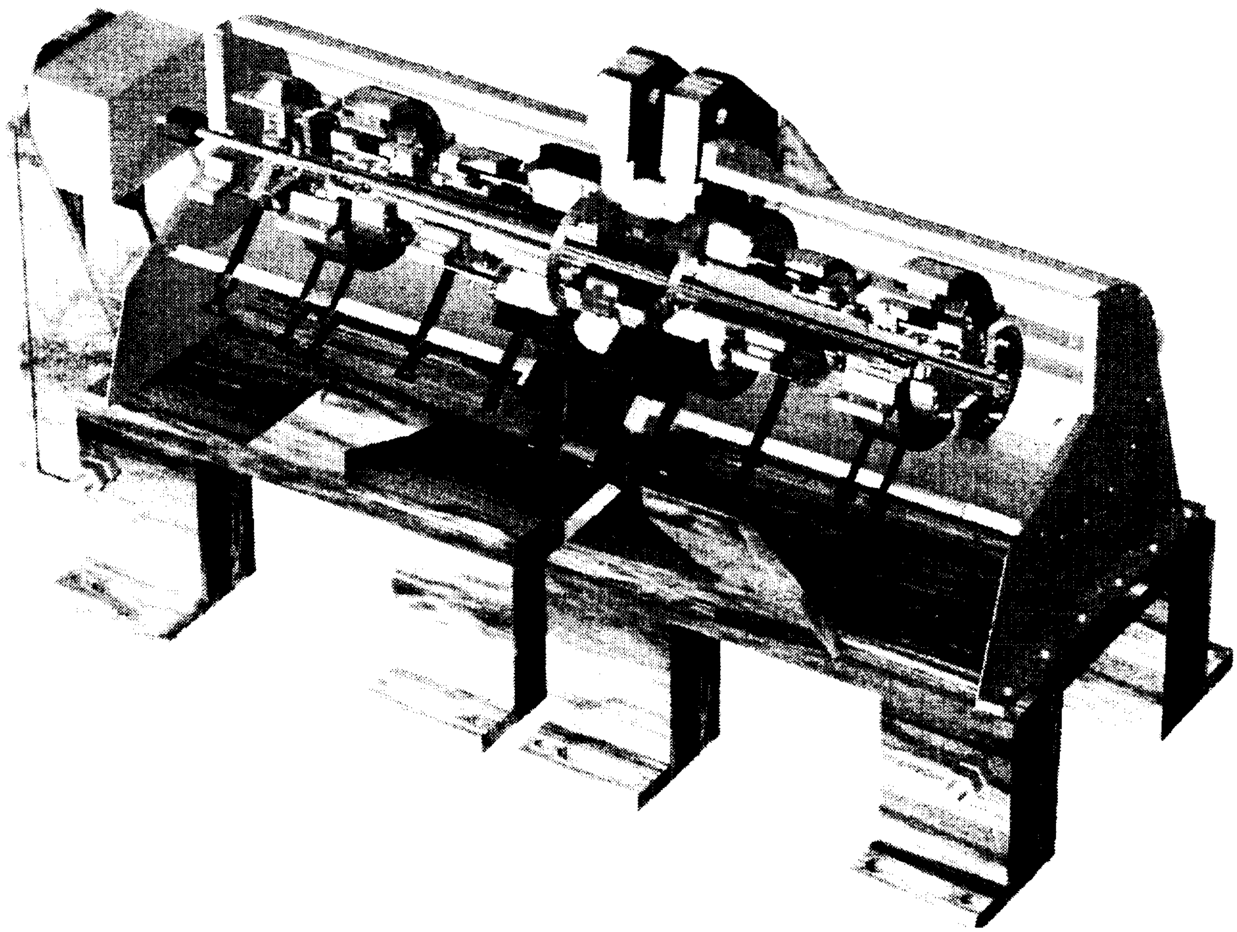
High-Temperature Magnetic Bearings for Gas Turbine Engines

Magnetic bearings are the subject of a new NASA Lewis and U.S. Army thrust with significant industry participation, and cooperation with other Government agencies. The NASA/Army emphasis is on high-temperature applications for future gas turbine engines. Magnetic bearings could increase the reliability and reduce the weight of these engines by eliminating the lubrication system. They could also increase the DN (diameter of the bearing times the rpm) limit on engine speed and allow active vibration cancellation systems to be used, resulting in a more efficient, "more electric" engine. Finally, the Integrated High Performance Turbine Engine Technology (IHPTET) Program, a joint Department of Defense/industry program, has identified the need for a high-temperature (1200 °F) magnetic bearing that could be demonstrated in their Phase III engine.

This magnetic bearing is similar to an electric motor. It has a laminated rotor and stator made of cobalt steel. Wound around the stator's circumference are a series of electrical wire coils which form a series of electric magnets that exert a force on the rotor. A probe senses the position of the rotor, and a feedback controller keeps it centered in the cavity. The engine rotor, bearings, and casing form a flexible structure with many modes. The bearing feedback controller, which could cause some of these modes to become unstable, could be adapted to varying flight conditions to minimize seal clearances and monitor the health of the system.

Cobalt steel has a curie point greater than 1700 °F, and copper wire has a melting point beyond that. However, practical limitations associated with maximum magnetic field strength in the cobalt steel and the stress in the rotating components limit the temperature to about 1200 °F. The objective of this effort is to determine the temperature and speed limits of this magnetic bearing operating in an engine. Our approach is to use our in-house experience in magnets, mechanical components, high-temperature materials, and surface lubrication to build and test a magnetic bearing in both a rig and an engine. Testing will be done at Lewis or through cooperative programs in industrial facilities.

During the last year, we made significant progress. We have a cooperative program with Allison Engine to work on a high-temperature magnetic thrust bearing. During this program, we uncovered a problem with the conventional design of the magnetic thrust bearing. Because the thrust bearing is not laminated, it causes eddy currents that severely reduce the bandwidth. Also, we worked at Allison to bring their high-temperature magnetic bearing rig to full speed. We predicted both in-house and Allison magnetic bearing stability limits, and we tested a high-temperature displacement probe. Our flexible casing rig is being converted to a high-temperature magnetic bearing rig (see the figure). Testing should start in the third quarter of 1997. Our plan is to develop a high-temperature, compact wire insulation and to fiber reinforce the core lamination to operate at higher temperature and DN values. We plan to modify our stability analysis and controller theory by including a nonlinear magnetic bearing model. We are developing an expert system that adapts to changing flight conditions and that diagnoses the health of the system. Then, we will demonstrate the bearing on our rotordynamics rig and, finally, in an engine.



NASA Lewis' 1000 °F Magnetic Bearing Test Rig.

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Neural Network Control of a Magnetically Suspended Rotor System

Magnetic bearings offer significant advantages because they do not come into contact with moving parts during operation, a feature that can reduce maintenance. Higher speeds, no friction, no lubrication, weight reduction, precise position control, and active damping make them far superior to conventional contact bearings. However, there are technical barriers that limit the application of this technology in industry. One of them is the need for a nonlinear controller that can overcome the system nonlinearity and uncertainty that are inherent in magnetic bearings. A neural network was selected for a nonlinear controller because it generates a neural model without any detailed information regarding the internal working of the magnetic bearing system. It can be used even for systems that are too complex for an accurate system model to be derived. A feed-forward architecture with a back-propagation learning algorithm was selected because of its proven performance, accuracy, and relatively easy implementation.

The neural network plant emulator was first trained to emulate a theoretical model of the nonlinear plant. A discrete theoretical model of the plant dynamics in state-space notation was used to choose the present states of the plant (rotor displacement and velocity) and the plant input (control current) to be the input to the emulator. The next states, the rotor displacement and velocity after one sample time, were chosen to be the output from the plant emulator. During the learning procedure, we minimized the errors between the actual network output and the desired values by upgrading the weights. After training, the neural emulator perfectly predicted the next states (delayed by one sample time) of the magnetic bearing system for the current states and the control force, which were not in the training sample data.

Our second step was to use the trained neural emulator to train the neural network controller that makes the whole system meet conventional performance specifications on such parameters as the bandwidth, settling time, and overshoot. We wanted the controller to take the current magnetic bearing states $\bar{x}(t)$ and demand r as input parameters and to output a control force $u(t)$ to the magnetic bearing system. These current state values should make the magnetic bearing's next state vector $\bar{x}(t+1)$ identical to that defined by the desired linear reference system, satisfying performance specifications in either the frequency or time domain.

Figure 1(a) shows the Bode plot of a simple second-order linear reference model derived from frequency domain specifications; figure 1(b) shows the closed-loop magnetic bearing system after training. Both are almost identical even after 200 training epochs. Another neural controller based on time domain specifications was trained and tested by simulating its response for the initial condition and comparing the results to the actual magnetic bearing response (fig. 2). The neural network controller was so accurate that it perfectly overlapped the magnetic bearing response (+ markers).

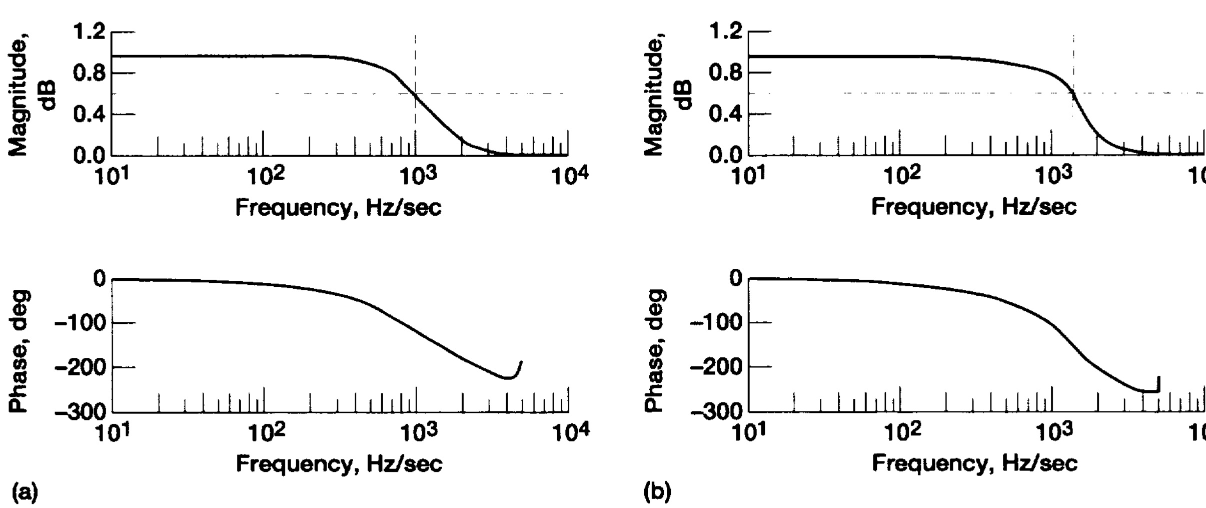

Figure 1.—Bode plots of desired and neural network models in the frequency domain, showing averaged transfer function. (a) Simple second-order linear reference model for a frequency domain of peak magnitude, m_p, 1.1, and cutoff frequency, w_c, 1000 Hz. (b) Trained closed-loop system.

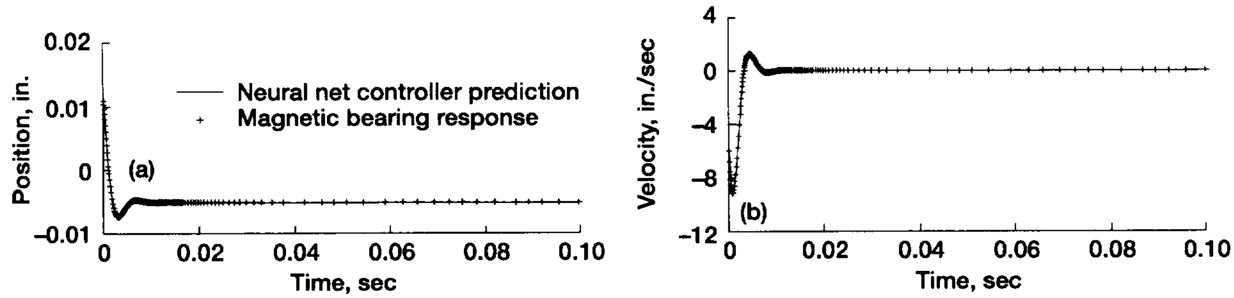

Figure 2.—Desired and actual response in the time domain. (a) Simple second-order linear reference model response for percent of overshoot, P_o, 4.3 percent, and settling time, T_s, 0.0001 sec. (b) Trained closed-loop system response for initial position, x_0, 0.0011 in.; initial velocity, $\dot{x}_0$, –6 in./sec; and reference position, r_f, –0.005 in.

In summary, a neural network controller that circumvents the magnetic bearing's nonlinearity was developed and successfully demonstrated on a small Bentley-Nevada magnetic bearing rig. The neural plant emulator and neural controller were so accurate that the neural network controller did a near perfect job of making the nonlinear magnetic bearing system act like the linear reference model. This novel approach demonstrated the feasibility of using it for advanced turbomachinery systems with large magnetic bearings with unknown dynamics.

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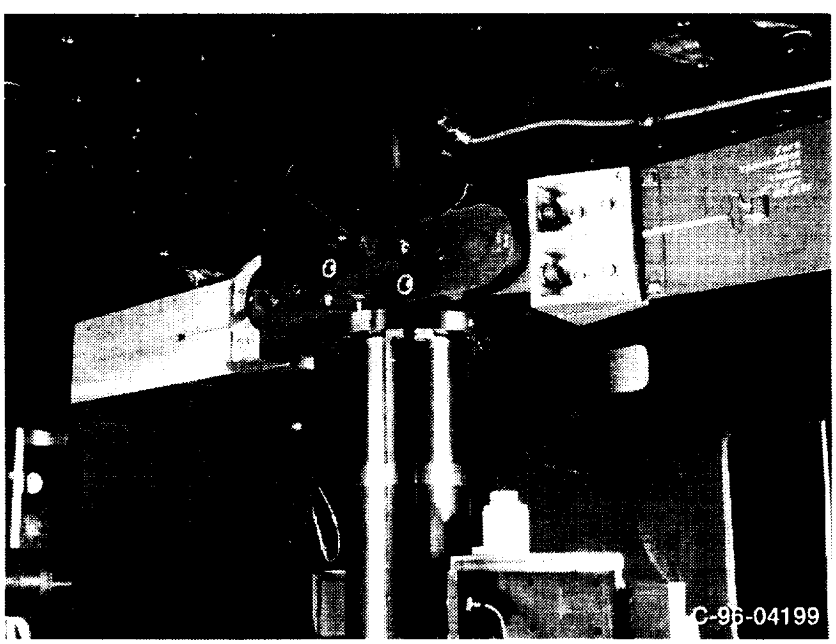
Damping Experiment of Spinning Composite Plates With Embedded Viscoelastic Material

One way to increase gas turbine engine blade reliability and durability is to reduce blade vibration. It is well known that vibration reduction can be achieved by adding damping to metal and composite blade-disk systems. As part of a joint research effort of NASA Lewis and the University of California, San Diego, an experiment was done to investigate the use of integral viscoelastic damping treatment to reduce the vibration of rotating composite fan blades. The objectives of this experiment were to verify the structural integrity of composite plates with viscoelastic material patches embedded between composite layers while under large steady forces from spinning and to measure the variation of damping and natural frequency with rotational speed.

Data were obtained from in-vacuum vibration spin experiments of flat and twisted graphite composite plates damped with 3M ISD 113 viscoelastic material patches embedded between composite layers. The photograph shows the rotor installation in the spin facility. The rotor has a tip diameter of 792 mm, and the plates have an aspect ratio of 3 and a chord of 76 mm. Damping was calculated from measured transfer functions from blade base acceleration to blade strain. Damping was repeatable, and there were no failures or delaminations of the plates. This is significant since 3M ISD 113 has a low creep modulus at room temperature and the plates had a centrifugal load of up to 28 000 g at the tip. Centrifugal stiffening was large for the plates and caused a significant drop in the damping ratios, but the viscoelastic material damping remained nearly constant. Even though the damping ratios decreased, they were always greater than 2 times the damping ratios of undamped control plates. Real fan blades have smaller increases in natural frequencies with rotational speed, and therefore, their decrease in fan blade damping ratio should be smaller than that measured in this experiment.

From the results, we conclude that the presence of centrifugal forces, which are well known to increase blade bending stiffness and corresponding natural frequencies, will decrease the damping ratios. This phenomenon occurs because as the blade stiffens the corresponding modal strain levels and strain energy in the damping material decrease, thus decreasing the modal damping ratios. To further improve damping, designers will need to consider how to increase the strain energy level in the viscoelastic material, such as using a stiffer viscoelastic damping material than used here. This study reveals not only the potential of integral viscoelastic material damping in composite fan blades, but also illustrates that there are technical challenges that still must be overcome before it can be effectively used as a design option.



Viscoelastic damped composite plates in NASA Lewis' Dynamic Spin Rig.

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Improved Dual-Clearance Squeeze Film Damper for High Loads

Squeeze film dampers are widely used to control vibration in high-speed rotating machinery. However, a conventional squeeze film damper will be overloaded by an imbalance appreciably above the design value (e.g., due to turbine blade loss) and will no longer be effective in controlling vibration amplitudes and bearing forces. The dual-clearance damper (fig. 1), characterized by two oil films separated by a sleeve, overcomes this problem. The sleeve is fixed in place for normal operation; the thin inner damper film (typically about 0.1 mm) provides all the damping. In the event of rotor blade loss or another event that increases the imbalance significantly, the sleeve is released (in the illustration, by shearing the pins holding it) and the outer damper film becomes active. The two films then operate in series; that is, the bearing load is transmitted first through the inner film, then through the sleeve and outer film to the machine structure. The outer film has a larger clearance than the inner film to accommodate the larger vibration amplitude necessarily accompanying the higher imbalance. Sleeve mass, which was not accounted for in previous analyses, was found to be detrimental to damper performance. Inclusion of a spring support for the sleeve mitigated the effect of sleeve mass and markedly improved the performance of the dual-clearance damper.

A dual-clearance damper was designed for a five-mass flexible rotor system. The rotor, 62-cm long with a mass of 5.7 kg, was assumed to have an imbalance of 290 g-cm distributed over the rotor length. For all cases in which sleeve mass was accounted for, the mass was taken as 360 g, about what it would be for aluminum.

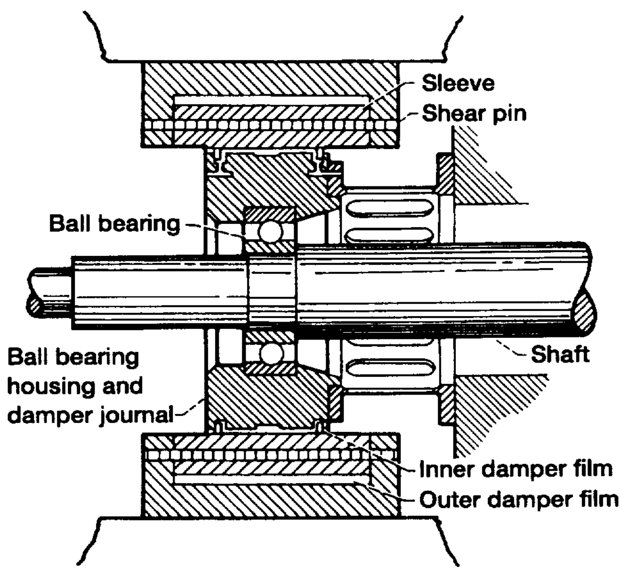

Figure 1.—Dual-clearance squeeze film damper.

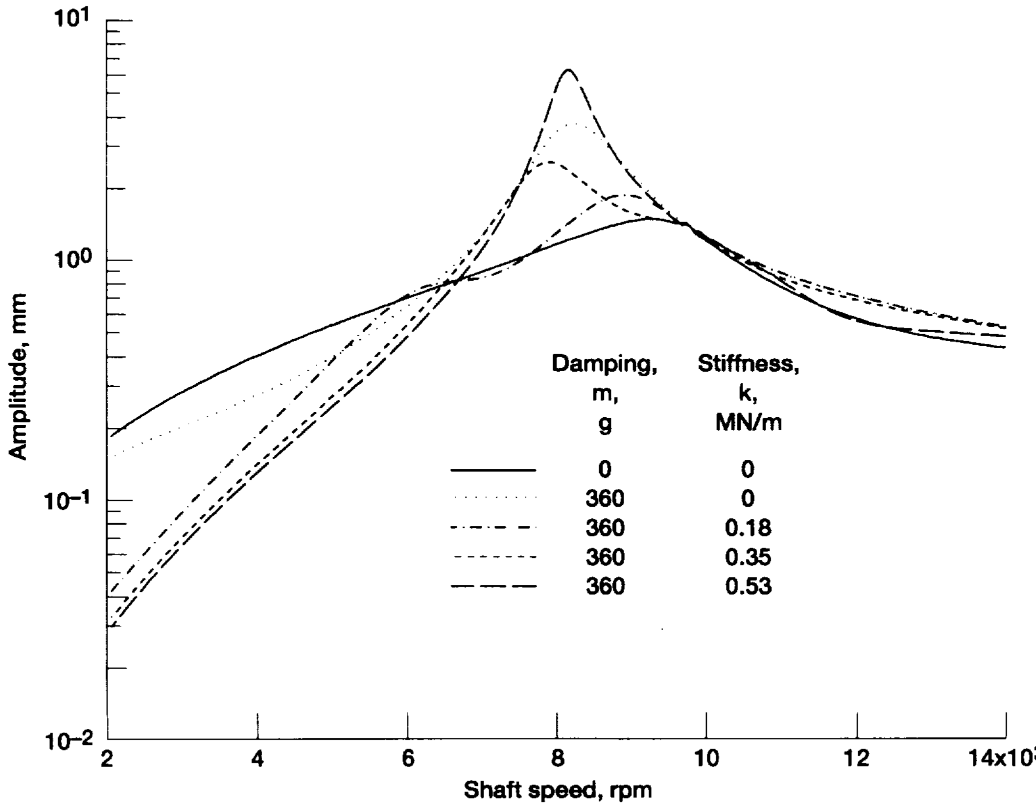

Figure 2.—Rotor midspan amplitude.

For this rotor system, vibration amplitude is largest at midspan. Figure 2 plots midspan amplitude over a range of speeds for several conditions. The solid line is for the previously analyzed case neglecting sleeve mass. Vibration is very close to that obtained with an ideal damper whose stiffness and damping are independent of amplitude and speed. The dotted line includes sleeve mass but no spring support; vibration is somewhat lower at low speeds, but rises considerably higher at the rigid-support critical speed of 8280 rpm. Three spring stiffnesses were then investigated. A stiffness of 0.18 MN/m (the dot-dash line) produced the lowest amplitudes overall; peak vibration was not much higher than for the massless sleeve. Higher spring stiffnesses resulted in progressively higher peak amplitudes. The dual-clearance damper, with proper spring support of the sleeve, holds promise to provide good rotordynamic control of flexible shaft systems at both normal and extraordinarily large imbalances.

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User's Guide for MSAP2D: An Euler Flutter and Forced Response Analysis Code for Multistage Turbomachinery

Most of the current aeroelastic analyses for turbomachines analyze only one blade row (i.e., an isolated blade row). The multistage effects (effects due to the presence of other blade rows) are neglected or are included in only an approximate manner. Prediction of the flutter and forced response characteristics of turbomachinery blades requires an accurate analysis of the multibladed-row turbomachine as a single unit. Toward this goal, we developed an aeroelastic program, MSAP2D (Multistage Aeroelastic Program—Two-Dimensional). This program can be used for unsteady aerodynamic and aeroelastic analyses of multiblade rows, such as compressor or turbine stages. It also can be used for an isolated blade row.

To obtain the unsteady aerodynamic forces, MSAP2D uses a finite volume method with a combination of flux vector splitting and flux difference splitting to solve two-dimensional Euler equations. The Euler solution scheme is third-order accurate in space and second-order accurate in time. The flow equations are solved on one or more passage-centered H-grids. After the interior of the computational domain is updated, the interface boundary between the blade rows, which is handled as an additional fluid boundary, is updated explicitly. The structural model is a typical section with bending and torsional degrees of freedom for each blade in the blade row and for all blade rows. Newmark's method is used to solve the aeroelastic equations in the time domain. The program has been calibrated for several examples.

A guide has been written to help users prepare the input data file required by MSAP2D. Input data are completely described, and input and output data are given for three examples from published papers. References are provided in this user's guide for detailed explanations of the aerodynamic analysis, the numerical algorithms, and the aeroelastic analysis. A job control file for executing the program on Cray YMP computers is also given.

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User's Manual for ASTROP2, Version 2.0: A Program for Aeroelastic Stability Analysis of Multiblade Structures

Flutter is an aeroelastic instability that must be considered in the safe design of an aircraft engine. Flutter in fan, compressor, or turbine blading can delay the development of new engines and, consequently, increase developmental costs. The aeroelastic code ASTROP2 (Aeroelastic Stability and Response of Propulsion Systems—Two-Dimensional Analysis) can analyze the flutter of rotating propfan, compressor, and turbine blades. It was developed for a project aimed at designing advanced propellers that can cruise at Mach 0.8.

ASTROP2, which was developed for use in a design environment, can be used on a desktop workstation. To formulate the aeroelastic eigenvalue equations, the code uses strip theory to combine blade structural characteristics with the unsteady aerodynamic forces due to vibrating blades. The flutter stability information, flutter frequency, and damping are inferred from the eigenvalues obtained from these equations. In ASTROP2, the unsteady aerodynamic forces are obtained from two-dimensional cascade theories. The structural characteristics are obtained from a three-dimensional structural model. An interface with NASTRAN is included in the program; however, the interface can be modified to suit any structural program. ASTROP2 can be used by engine companies of any size to assess the flutter stability of any engine. The program requires minimum computational resources.

In version 2.0, flutter analysis is performed by two separate programs: (1) 2DSTRIP, which calculates structural dynamic information at selected stations, called strips, and (2) 2DASTROP, which calculates unsteady aerodynamic force coefficients as well as aeroelastic stability. Because the programs are independent, users can check structural models and aerodynamic models separately. In version 1.0, these two functions were performed by a single program. Other improvements to version 2.0 include an option to account for counter rotation, improved numerical integration, accommodation for nonuniform inflow distribution, and an interactive scheme to obtain flutter frequency convergence. ASTROP2 was written in FORTRAN 77. Version 2.0 has been implemented on a Cray computer and a Silicon Graphics Indigo2 workstation. It is available through COSMIC (University of Georgia, 382 Broad Street, Athens, GA 30602–4272, (706) 542–3265 (voice), (706) 542–4807 (fax), service@cosmic.uga.edu, http://www.cosmic.uga.edu/).

A guide has been written to help users prepare the input data file required by version 2.0 of ASTROP2. It completely describes the input data and gives input and output data for a propfan that showed flutter instability during wind tunnel testing. References are provided in this user's guide for detailed explanations of the aerodynamic analysis, the numerical algorithms, and the aeroelastic analysis. A job control file for executing the program on Cray YMP computers is also given.

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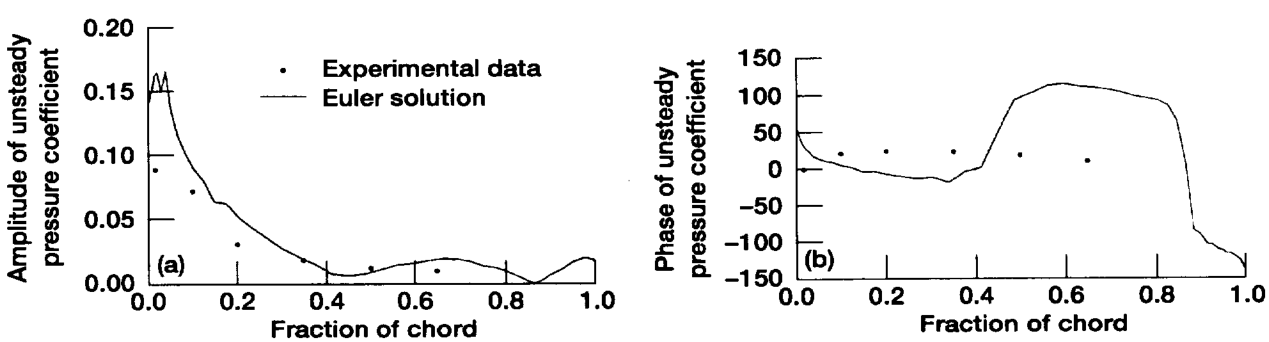
Using an Euler Aeroelastic Solver for the Gust and Structural Response Analysis of a Two-Dimensional Cascade

Forced response from nonuniform unsteady flow (gust) due to the presence of upstream blade rows, and aeroelastic stability (flutter) are two important areas to be considered in the safe design of turbomachines. To the authors' knowledge, no single program mentioned in the open literature calculates the gust response in addition to rotor/stator interaction and structural (aeroelastic) response. To address this need, we modified the multistage aeroelastic analysis program MSAP2D (Multistage Aeroelastic Program—Two-Dimensional) to include gust response analysis. Modifications included prescribing unsteady inflow conditions at the inlet and using one-dimensional nonreflecting boundary conditions. We validated the modifications by comparing the predicted unsteady pressure and phase angles with measured data.

To obtain the unsteady aerodynamic forces, MSAP2D uses a finite volume method with a combination of flux vector splitting and flux difference splitting to solve two-dimensional Euler equations. This Euler solution scheme is third-order accurate in space and second-order accurate in time. The flow equations are solved on one or more passage-centered H-grids. The structural model is a typical section with bending and torsional degrees of freedom for each blade in the cascade. Newmark's method is used to solve the aeroelastic equations in the time domain.

Parts (a) and (b) of the figure show the amplitude and phase, respectively, of the unsteady pressure coefficient plotted with the chord on the lower surface of a turbine airfoil tested at Mach 0.27. The flow is entering axially; and it turns about 40°. The steady inflow angle is 2.98°, and the reduced frequency of oscillation based on chord is 10.0. The amplitudes of the unsteady pressures compare reasonably well with measured data. Phase comparisons are fair in regions where amplitudes are higher but are poor for areas with lower amplitudes. However, predictions at Mach 0.2 for the upper surface showed poor to fair correlation, indicating that further investigation is needed.



Unsteady pressure coefficients and their phase angles. (a) Variation of unsteady pressure coefficient at Mach 0.27. Reduced frequency based on chord, 10.0; angle of attack, 2.98°; gap-to-chord ratio, 0.9744; phase angle, 0.0°. (b) Variation of the phase angle of the unsteady pressure.

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Flutter Analysis of Ducted Rotors

An aeroelastic analysis procedure, DuctE3D (Ducted Fan Euler—Three-Dimensional), has been developed to investigate the flutter of turbomachine configurations. In the analysis, the unsteady airloads on vibrating blades are obtained from three-dimensional unsteady Euler equations, and the blades' structural properties are obtained from a three-dimensional finite element model. The duct is assumed to be infinitely long and structurally rigid. Any number of structural modes of blade vibration can be included in the analysis. The aeroelastic equations are formulated in the normal mode, and the frequency domain analysis technique is used to solve for flutter at all possible interblade phase angles. For verification, the analysis is applied to a ducted fan configuration obtained by enclosing a propfan within an infinite rigid duct.

DuctE3D uses an implicit-explicit hybrid scheme to solve the three-dimensional Euler equations. The scheme saves a large amount of CPU (central processing unit) time as well as memory requirements since only two matrix inversions are required as opposed to three for fully implicit schemes. For structural analysis, the normal mode approach is used and the hub and duct are assumed to be rigid. For flutter analysis, one of the blades is moved from steady state in a prescribed pulse motion and the resulting unsteady aerodynamic forces are on all the blades. These forces are then superposed, and an eigenvalue problem is solved to obtain the roots of the aeroelastic equation. The roots provide a measure of aerodynamic damping at the combined aeroelastic frequency. Negative aerodynamic damping indicates that the blade will extract energy from the surrounding air and will be unstable. Any number of normal modes can be included in the analysis. A single run is sufficient to provide the aeroelastic characteristics of the blades for each mode of interest at a particular flight condition.

We applied the analysis to an eight-bladed ducted fan obtained by enclosing the SR3C–X2 propfan in a rigid cylindrical duct. In the unducted configuration, the SR3C–X2 propfan showed flutter in NASA Lewis wind tunnel tests at a free-stream Mach number of 0.6 for an eight-bladed configuration operating at an advance ratio of 3.55 and a setting angle of 61.2°. The analysis, which was carried out at a free-stream Mach number of 0.5, used the first three normal modes for a tip gap of 0.4 percent of the rotor radius. The analysis was used to obtain the unsteady generalized forces on all the blades; then, a postprocessing program was used to solve the eigenvalue problem for the aeroelastic characteristics. The variations of generalized forces, F_{11}, with time are shown in figures 1 and 2. By observing the generalized forces, we found that the amplitudes of forces fall off rapidly as one moves away from the reference blade, the blade being moved. Thus, we argued that if only the blades in close proximity to the reference blades were included in the analysis, say four blades, we should be able to calculate the characteristics of an eight-bladed rotor with reasonable accuracy. This could reduce computational costs by at least 50 percent. To test this, we calculated the generalized forces for the eight-bladed rotor by applying the periodicity across only four blade passages. Figure 2 shows the resultant eigenvalue plot for both the eight- and four-bladed analyses. The results at this stage are not very encouraging. Even though the four-bladed analysis accurately predicts the interblade phase angles it is valid for, the other interblade phase angles are poorly predicted. We believe that this method requires more investigation.

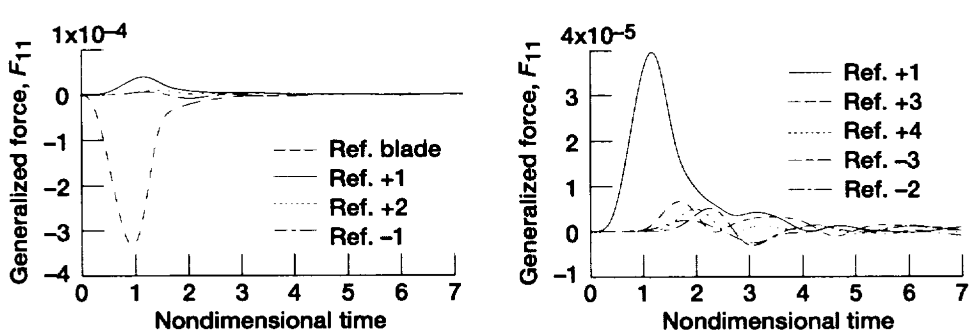

Figure 1.—Time history of generalized forces of the eight-bladed fan. Free-stream Mach number, 0.5; advance ratio, 3.55; setting angle, 61.2°. (The reference blade is the blade being moved. Other blades are numbered clockwise (+) or counter-clockwise (−) from the blade being moved.)

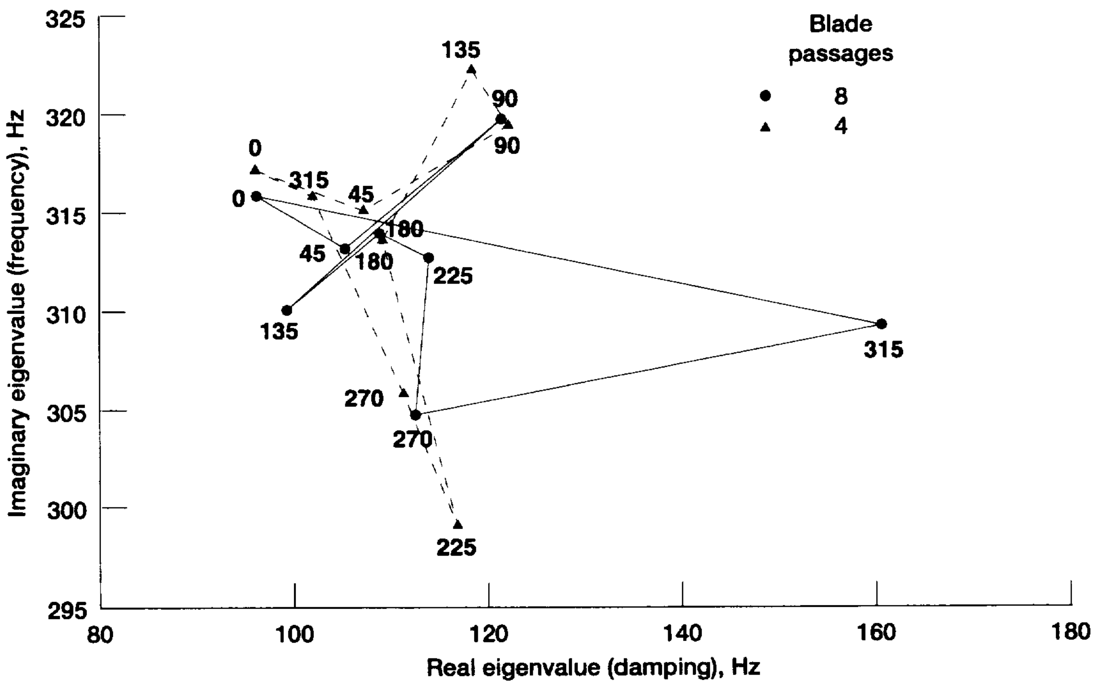

Figure 2.—Eigenvalue plot for eight- and four-blade analyses of the eight-bladed fan. Free-stream Mach number, 0.5; advance ratio, 3.55; setting angle, 61.2°.

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TURBO–AE: An Aeroelastic Code for Propulsion Applications

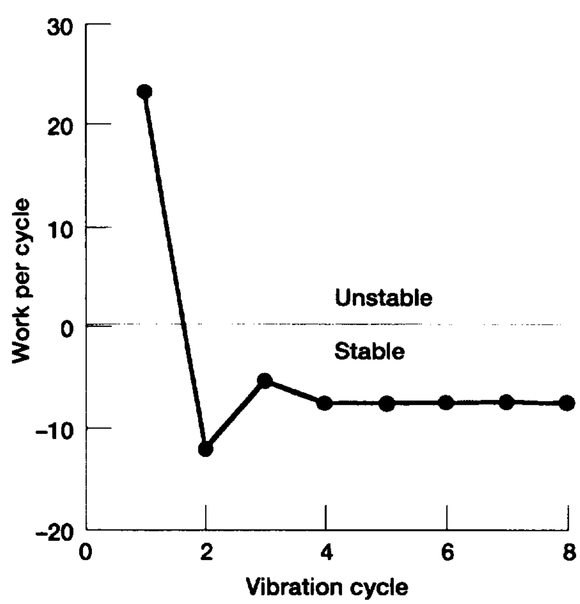
NASA's Advanced Subsonic Technology (AST) program seeks to develop new technologies to increase the fuel efficiency of commercial aircraft engines, improve the safety of engine operation, and reduce emissions and engine noise. With the development of new designs for ducted fans, compressors, and turbines to achieve these goals, a basic aeroelastic requirement is that there should be no flutter or high resonant blade stresses in the operating regime. An accurate prediction/analysis code is needed to verify the aeroelastic soundness of the design. Such a three-dimensional, viscous propulsion aeroelastic code, TURBO–AE, is being developed at NASA Lewis.

TURBO–AE is based on a three-dimensional, unsteady, aerodynamic Euler/Navier-Stokes turbomachinery code, TURBO, developed under a grant from NASA Lewis. TURBO–AE can model viscous flow effects that play an important role in certain aeroelastic problems, such as flutter with flow separation, stall flutter, and flutter in the presence of shock and boundary-layer interaction. Free vibration modes in a vacuum are used to model the structural dynamics of the blade. A finite-element analysis code, such as NASTRAN, is used to calculate the mode shapes and frequencies.

To determine aeroelastic (flutter) stability, we used a work-per-cycle approach. With this approach, the motion of the blade is prescribed to be a harmonic vibration in a specified, normal mode in a vacuum. During a vibration cycle, the aerodynamic forces acting on the vibrating blade and the work done by these forces on the vibrating blade are calculated. If positive work is being done on the blade by the aerodynamic forces, the blade is dynamically unstable, since it will extract energy from the flow, leading to an increase in the blade's oscillation amplitude.

Initial calculations were done for a configuration representative of the Energy Efficient Engine fan rotor. The graph shows the work per cycle after each cycle of vibration. Work per cycle does not vary much after the fourth cycle of blade vibration. The negative sign of the converged work per cycle shows that the fan blade is dynamically stable and will not flutter.

TURBO–AE provides a useful aeroelastic prediction/analysis capability for engine manufacturers. It will reduce design cycle time by allowing new blade designs to be verified for aeroelastic soundness before blades are built and tested. With this prediction capability, it will be possible to build thinner, lighter, and faster rotating blades without encountering aeroelastic problems like stall flutter and high-cycle fatigue due to forced vibrations.



Aeroelastic work per cycle for blade vibrating in the first mode.

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Integrated Fiber-Optic Light Probe: Measurement of Static Deflections in Rotating Turbomachinery

At NASA Lewis, an integrated fiber-optic light probe system was designed, fabricated, and tested for monitoring blade tip deflections, vibrations, and to some extent, changes in blade tip clearances in a turbomachinery fan or a compressor rotor. The system comprises a set of integrated fiber-optic light probes that are positioned to detect the passing blade tip at the leading and trailing edges. In this configuration, measurements of both nonsynchronous blade vibrations and steady-state blade deflection can be made from the timing information provided by each light probe—consisting of an integrated fiber-optic transmitting channel and a numerical aperture receiving fibers, all mounted in the same cylindrical housing. With integrated fiber-optic technology, a spatial resolution of 50 μm is possible while the outer diameter is kept below 2.5 mm. In addition, one fiber sensor can monitor changes in blade tip clearance of the order of 10 μm. To evaluate these probes, we took measurements in a single-stage compressor facility and an advanced fan rig in NASA Lewis' 9- by 15-Foot Low-Speed Wind Tunnel.

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Feasibility of Accelerated Testing of Mechanical Systems Through the Use of Neural Network Models

Verification testing is an important aspect of the design process for mechanical mechanisms. Full-scale, full-length life testing is typically used to qualify any new component for use in space. However, as the required life specification is increased, full-length life tests become more costly and lengthen development time. In addition, this type of testing becomes prohibitive as the mission life exceeds 5 years, primarily because of the high cost and slow turnaround time for new technology. As a result, accelerated testing techniques are needed to reduce the time required for testing mechanical components.

Current accelerated testing methods typically consist of increasing speeds, loads, or temperatures to simulate a high cycle life in a short period of time. However, two significant drawbacks exist with this technique. The first is that it is often not clear what the accelerated factor is when the operating conditions are modified. Second, if the conditions are changed sufficiently (an order of magnitude or more), the mechanism is forced to operate out of its design regime. Operation in this condition often exceeds material and mechanical system parameters and renders the test meaningless.

We theorized that neural network systems might be able to model the operation of a mechanical device. If so, the resulting neural network models could simulate long-term mechanical testing with data from a short-term test. This combination of computer modeling and short-term mechanical testing could be used to verify the reliability of mechanical systems, thereby eliminating the costs associated with long-term testing. Neural network models could also enable designers to predict the performance of mechanisms at the conceptual design stage by entering the critical parameters as input and running the model to predict performance.

The purpose of this study was to assess the potential of using neural networks to predict the performance and life of mechanical systems. To do this, we generated a neural network system to model wear obtained from three accelerated testing devices: (1) a pin-on-disk tribometer, (2) a line-contact rub shoe tribometer, and (3) a four-ball tribometer. Critical parameters such as load, speed, oil viscosity, temperature, sliding distance, friction coefficient, wear, and material properties were used to produce models for each tribometer.

The study showed that neural networks were able to model these simple tribological systems, illustrating the feasibility of using neural networks to perform accelerated life testing on more complicated mechanical systems (e.g., bearings). Figure 1 compares actual wear data generated on a rub shoe tribometer with data that were generated from a neural network. As the figure illustrates, the correlation is very good.

Neural networks also can be used to predict input variables for conditions that have not been run experimentally. Figure 2 is a neural-network-generated three-dimensional plot of wear rate (for the pin-on-disk tribometer) as a function of sliding distance and sliding speed. The figure depicts the wear rate values that would be obtained for different distances and speeds.

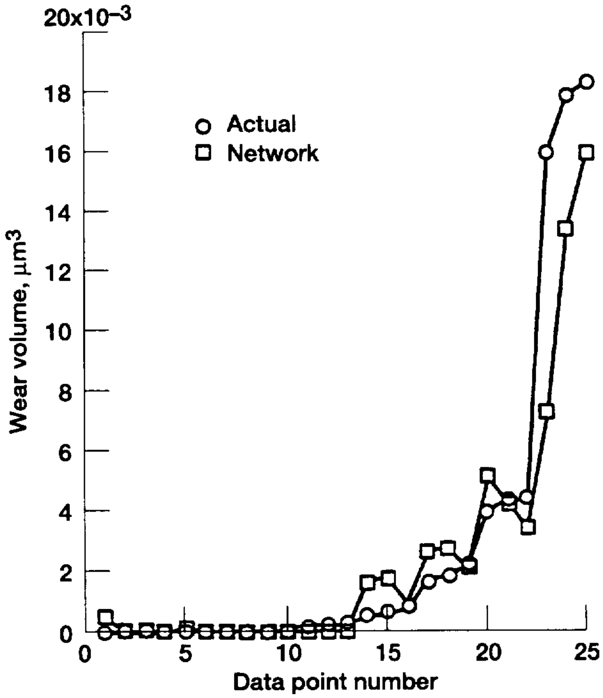

Figure 1.—Comparison of previously unknown rub shoe wear volumes (actual data) to those of a neural network model approximation.

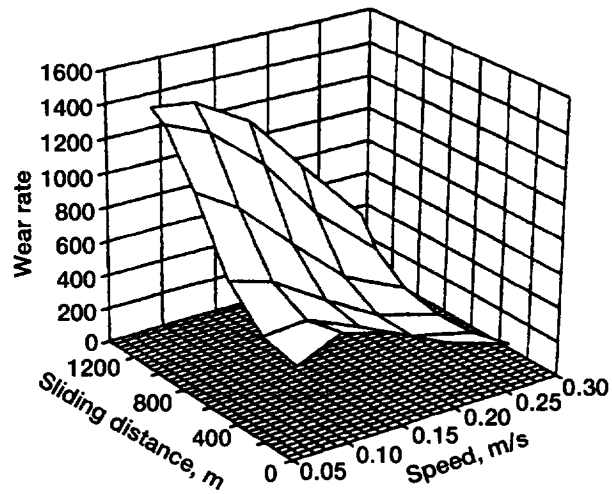

Figure 2.—Three-dimensional plots generated from a neural network model illustrating the relationship between speed, load, and pin-on-disk wear rate.

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13. ABSTRACT *(Maximum 200 words)*

This publication contains a collection of fiscal year 1996 research highlights from the Machine Dynamics Branch at NASA Lewis Research Center. Highlights from the branch's major work areas—Turbomachinery Aeroelasticity, Vibration Control and Magnetic Suspension Systems, Dynamic Systems Response and Analysis, and Computational Structural Methods—are included in the report as well as a listing of the fiscal year 1996 branch publications.

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